

Why Galaxies Care about Post-AGB stars

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Abstract. Post-AGB stars evolve on a very fast track and hence not many are known. Their spectral properties make them, in principle, ideal objects to test our theories on the late phases of stellar evolution. This has, however, proven much more difficult than anticipated, mainly because the morphological, dynamical and chemical diversity in Galactic post-AGB stars is very large indeed. Here I focus on recent results and touch upon the bright near future of post-AGB research.

1. Introduction: Shining Examples

Very detailed studies of individual objects are quite common in the astronomical literature of post-AGB stars. Shining examples are, among others, the Egg Nebula (AFGL 2688), with 747 references in ADS on 29/10/2010; the Calabash Nebula (OH 231.8 +4.2 = QX Pup), 411 references; and the Red Rectangle (HD 44179), 523 references. Despite these thorough studies, there is by no means a consensus on how these individual objects are connected by evolutionary channels. More generally, the sample of known Galactic post-AGB stars (Suárez et al. 2006; Szczerba et al. 2007) is not well connected via detailed theoretical evolutionary channels to the asymptotic giant branch (AGB) nor to the subsequent planetary nebula (PN) phase (Van Winckel 2003).

Additionally one of the most popular issues which govern the discussion in the research community on the final evolution of low- and intermediate-mass stars is the impact of binarity on our global understanding of these late stellar evolutionary phases. Confirmed or suspected classes of evolved binaries are so prominent (and so poorly understood), that our understanding of the final phases of single stars may also very well be confused.

During their evolution off the AGB, the central objects are subject to drastic changes on a very short timescale (Vassiliadis & Wood 1993; Blocker 1995): in $\sim 10^4$ – 10^5 years, the radius changes from several AU down to the final radius of the white dwarf (WD). The effective temperature of the central object changes from 3000 K to some 100 000 K. The wind properties of the rapidly evolving central stars will also change dramatically, and in the last decade it has become clear that the shaping of the circumstellar envelope starts very early after the AGB and much earlier than was generally acknowledged (Balick & Frank 2002; Sahai et al. 2007). The objects will also pass the high-luminosity end of the population II Cepheid instability strip, and hence many post-AGB stars of intermediate spectral type will pulsate.

Post-AGB stars emit over a very wide range of the electromagnetic spectrum and their study requires a multi-wavelength approach. The outline of this paper follows the sessions of the conference. In Section 2, I highlight their chemical diversity and show

also that common inhabitants in post-AGB samples may very well be binaries. In Section 3 I focus on the recently identified post-AGB stars in extragalactic environments. I end this contribution by listing some potentially very rewarding future developments in post-AGB research. In what follows I will use the general term “post-AGB stars” and do not restrict this contribution to the objects with resolved circumstellar material, which are generally dubbed the proto-planetary nebulae (PPNe). I will not focus on the shapes and shaping of PPNe and refer the interested reader to the proceedings of the recent conference on Asymmetric Planetary Nebulae (Zijlstra et al. 2011).

2. Common Inhabitants

Post-AGB photospheres bear witness to the total chemical changes induced by the dredge-ups during the whole stellar evolution. A major change is expected to occur during the AGB phase by the third dredge-up phenomenon. During the relaxation period after a thermal pulse, products of the internal nucleosynthesis can be brought to the surface of the star, while at the same time fueling the synthesis of heavy elements by inducing protons into the intershell. The formation of ^{13}C and the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction can initiate the slow neutron-capture reaction chains (the *s*-process) deep in the stellar interior. For more massive stars and/or at the hotter parts of the He shell-flash, the ^{22}Ne neutron source will become active (see Karakas in these proceedings). Synthesis by the *s*-process is thought to be an important contributor to the cosmic abundances past the iron peak, and solar-type stars are very important contributors to this, as well as to the total carbon and nitrogen enrichment of the parent galaxy.

This rich nucleosynthesis is, however, only detected in a small subset of Galactic post-AGB stars, namely the post-Carbon stars (e.g. Van Winckel & Reyniers 2000; Reyniers et al. 2002; Reddy et al. 2002; Reyniers 2002). These also show a characteristic dust feature in their infrared spectra at $21\ \mu\text{m}$, which is only detected in circumstellar dust envelopes of carbon-rich post-AGB stars (e.g. Kwok et al. 1989; Hrivnak et al. 2010). The carrier of this feature is still a matter of debate.

Some post-AGB stars are the most *s*-process enriched objects known to date (e.g. Reyniers et al. 2004), while others are not enriched at all. This dichotomy is very strict, in the sense that mildly enhanced objects do not exist in current Galactic post-AGB samples (except for a few rather atypical objects). This is not expected, as a more gradual transition between non-enriched and enriched photospheres will occur, if the transition from an O-rich AGB to a C-rich AGB star happens over many thermal pulses. Stellar evolutionary AGB models cannot predict very well the minimum initial stellar mass for the third dredge-up to occur (see Stancliffe in these proceedings), and the dependence of the third dredge-up phenomenon on the metallicity, initial mass, and luminosity still remains very uncertain. Examples exist of very similar post-AGB stars (in metallicity, spectral type, infrared excess, etc.) with totally different photospheric abundance patterns. These results clearly illustrate that the third dredge-up phenomenon, and the associated partial mixing of protons invoked to explain the *s*-process nucleosynthesis, is still far from being fully understood.

Binary objects tend to have a totally different photospheric composition than suspected single objects, showing some degree of depletion of refractory elements in their photosphere: elements with a high dust condensation temperature are systematically under-abundant (e.g. Giridhar et al. 2005; Maas et al. 2005; Reyniers & Van Winckel 2007). In almost all depleted post-AGB objects, there is observational evidence that a

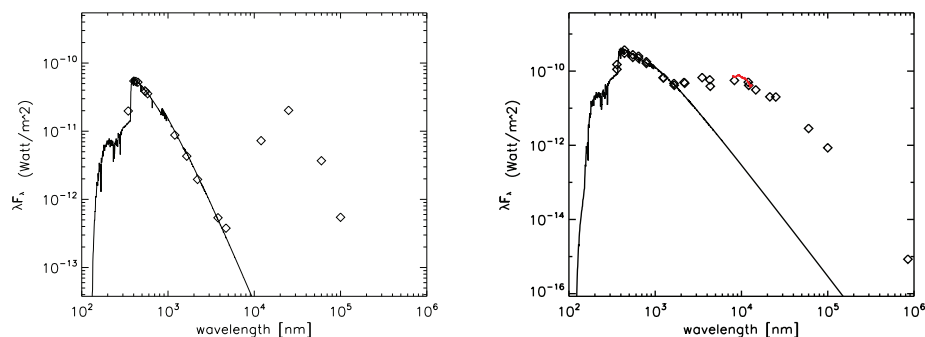


Figure 1. Spectral energy distributions of two clearly different post-AGB stars. The full lines are the appropriate Kurucz atmospheric models. The points indicate dereddened broad-band fluxes. *Left*: HD 187885, a carbon and *s*-process enhanced post-AGB star (Van Winckel, Waelkens, & Waters 1996b). *Right*: the SED of IRAS 08544-4431 (Maas et al. 2003), a binary with a resolved compact circumstellar disc (Deroo et al. 2007). The flux at sub-mm wavelengths indicate the presence of large circumstellar grains (De Ruyter et al. 2005).

stable circumbinary disc is present (De Ruyter et al. 2006) and we can use the typical infrared signatures of these circumbinary discs (see Figure 1) to discriminate between probable single stars and evolved binaries. The disc seems to be a prerequisite to obtain the photospheric depletion patterns by accretion of gas, cleaned from refractories by dust formation (Waters, Trams, & Waelkens 1992). Interferometric studies confirm the very compact nature of the circumstellar material (Deroo et al. 2006, 2007) and infrared spectroscopy shows the very high degree of processing of the dust grains in the discs (De Ruyter et al. 2005; Gielen et al. 2007, 2008) (see also Gielen, this conference).

Our radial velocity program is still on-going, but we indeed can confirm the suspected high binary rate: for non-pulsating objects with energy distributions pointing to a disc, a binary rate of 100% was found (Van Winckel et al. 2009). The companion stars are likely unevolved main-sequence stars, which do not contribute significantly to the energy budget of the objects. The orbits are now not in contact, but they are too small to have accommodated an AGB star. Our radial velocity monitoring program is still continuing with our new HERMES high-resolution spectrograph (Raskin et al. 2011). After a few more years of monitoring, this program will allow a good statistical overview of the orbital properties of these evolved binaries.

The global picture that emerges is that a binary star evolved in a system which is too small to accommodate a full grown AGB star. During a badly understood phase of strong interaction, a circumbinary dusty disc was formed, but the binary system did not suffer dramatic spiral-in. What we observe now is an F-G post-AGB supergiant in a binary system, which is surrounded by a circumbinary dusty disc. The objects were likely truncated during their ascent on the AGB branch. Observational hints for this truncated AGB evolution is that in all objects, the circumstellar dust in the disc is oxygen-rich (see Gielen, this conference). The formation of the disc occurred when the object was still an M star on the AGB. Subsequent thermal pulses may have occurred. In some objects double chemistry is detected in which the C-rich component is mainly limited to PAH emission (e.g. Gielen et al. 2009). This does not necessarily mean that the central object became a carbon star, as PAH emission is also found in environments

where dissociation of CO can liberate C atoms. Objects like the Red Rectangle (e.g. Witt et al. 2009) and HR 4049 (Geballe et al. 1989) display a richer C-rich dust and gas component.

In the Galaxy, post-AGB stars with observational evidence for a disc are a very significant fraction of all known post-AGB stars (Van Winckel 2003) and they are certainly common inhabitants.

3. Out There

So far relatively little focussed work can be found on extragalactic post-AGB stars (e.g. Wood & Cohen 2001; Kraemer et al. 2006; Reyniers et al. 2007). The first systematic searches were based on the data from microlensing projects. The light curve databases were scanned to find variability similar to luminous pulsating population II Cepheids such as RV Tauri stars (Alcock et al. 1998).

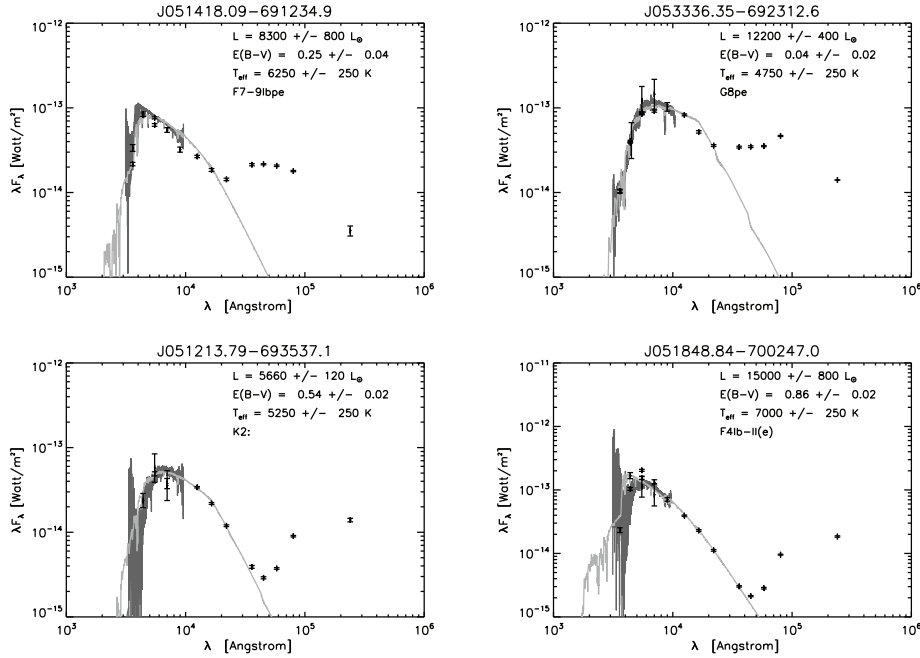


Figure 2. SEDs of post-AGB objects in the LMC (van Aarle 2010, submitted). The top panels show SEDs of disc sources while the bottom ones are more compliant with a detached shell.

A major step forward is offered by the large IR surveys which are deep and accurate enough to resolve individual extragalactic objects. The data release of the infrared SAGE-*Spitzer* survey of the LMC includes about 6.4 million sources detected with IRAC (several mid-infrared bands up to $8 \mu\text{m}$) and 60 000 objects detected at $24 \mu\text{m}$ (Meixner et al. 2006).

The systematic sample selection of post-AGB candidate stars in the LMC by van Aarle (submitted) is based on the second SAGE data release (September 2009), and we

searched for luminous, optically bright stars with infrared colours indicative of a past history of dusty mass loss.

To discriminate between genuine post-AGB stars and other objects with IR excesses such as luminous young stellar objects, PNe, dusty supergiants, etc., the integrated luminosity is used as a selection criterion as well. Moreover, to probe the spectral type of the central objects, a low-resolution optical spectral survey was performed at Siding Spring, Australia, and at SAAO (South Africa). The final catalogue consists of 1780 good candidate post-AGB stars of which 66 are well characterised with low-resolution spectra at this stage. About half of this sample show indications of a circumstellar disc rather than an expanding outflow! To prove that these are binaries will indeed be an observational challenge.

For the SMC, with its lower global metallicity, the third dredge-up enrichment is predicted to be stronger, as witnessed by the low-luminosity tail of the intrinsic carbon star luminosity function of the SMC (e.g. Lagadec et al. 2007). The sample selection of the SMC was based on the *Spitzer* S3MC survey (Bolatto et al. 2007) in a very similar way as was performed on the LMC data. So far, low-resolution optical data for 34 of the post-AGB candidates in the SMC have been registered.

Our observing proposal (PI: Peter Wood) for a full low-resolution spectral survey of all good candidates, using the wide-field, multi-object spectrograph at Siding Spring, has been accepted. The low resolution spectra will be used to constrain the spectral type of the central star so that SEDs can be determined with good accuracy.

4. Perspectives

Post-AGB research has often concentrated on very detailed astrophysical investigations of bright and often spectacular Galactic stars. These detailed studies of nearby objects are now expanded into the far-infrared with the *Herschel* satellite (see the papers of Groenewegen, Bujarrabal, and Wesson in these proceedings). The harvest of this unique facility is, at the time of the writing, still in its infancy. Theoretical interpretation in terms of stellar evolution has always been hampered, however, by poorly constrained distances. It is not often clear whether the very thoroughly studied objects are representative of a large population of stars or mere odd-balls which populate a very specific region in the complete parameter space.

With the advent of large-scale infrared surveys of nearby galaxies, the exploitation of unique extragalactic samples of post-AGB stars has yet to begin. The complete catalogues offer strong potential in the study of mass-dependent properties of post-AGB stars.

The potentials are illustrated in Figures 3 and 4, where sample spectra are shown together with the preliminary results of our photospheric chemical study. The strong spectral impact of *s*-process enhancement on the photospheric spectra of these objects is clear. Unlike AGB stars (see Abia, these proceedings), these spectra are dominated by atomic lines and overall are much cleaner than AGB photospheric spectra. Detailed and accurate photospheric abundances can therefore be traced, from CNO to the heaviest elements well beyond the Ba peak. A detailed comparison between theoretical enrichment models and the chemical composition of a large sample of post-AGB stars with well-constrained luminosities will be very rewarding. It will allow us to put stringent constraints on the dredge-up occurrence in function of metallicity and luminosity, as well as on the *s*-process nucleosynthesis itself and its associated mixing uncertain-

ties (see Karakas, these proceedings). The study of the connection between the large number of post-AGB stars and the PNe of the LMC and SMC (see Stanghellini, these proceedings) will become possible in the near future when the former catalogue is evaluated more completely with the low-resolution spectral survey.

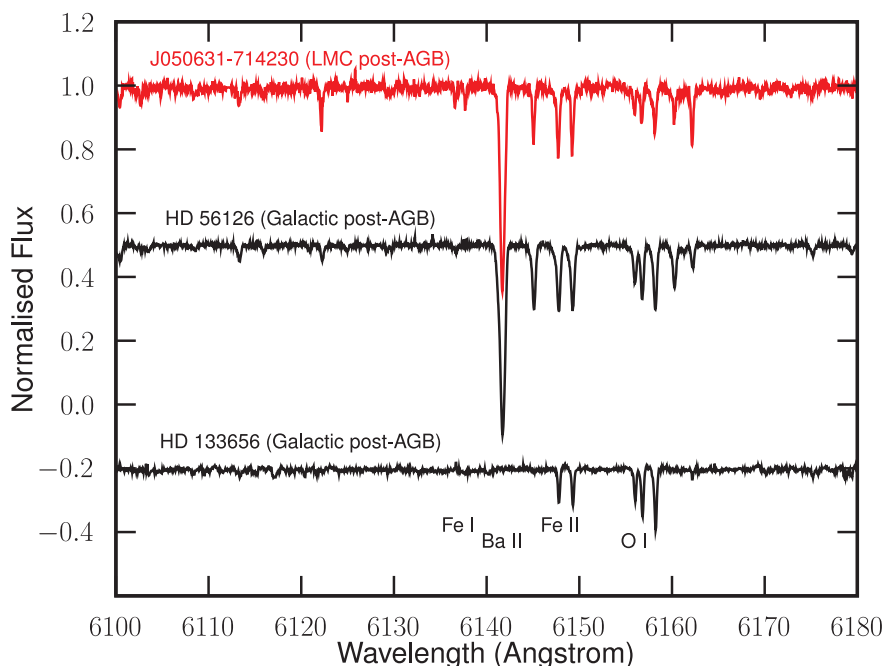


Figure 3. UVES spectra of three post-AGB stars in the region of the 6141 Å line of Ba II. The *top* spectrum is the LMC star J050631–714230, the SED of which is shown in Fig. 4. The *middle* spectrum shows HD 56126 (Hony et al. 2003), a Galactic carbon and *s*-process enriched post-AGB star. The *bottom* panel shows a non-enriched post-AGB stars HD 133656 (Van Winckel, Oudmaijer, & Trams 1996a) of similar spectral type and metallicity.

Additionally, the spectral complement to the SAGE survey, SAGE–SPEC (Kemper et al. 2010), and the spectral survey of the point-sources (Woods et al. 2011) will allow detailed comparison between the circumstellar gas and dust features with the often bright central star.

It is now generally acknowledged that post-AGB sources with discs are associated with binarity of the central stars. The discs have a longer infrared lifetime and the observed feedback from the disc onto the central star may very well prolong its post-AGB lifetime. The orbits obtained so far in the Galactic sample require that the central objects were subject to severe binary interaction processes when the primary was at giant dimensions. The discs in post-AGB stars are always associated with oxygen-rich dust. It did come as a surprise that stratified and very compact discs have been found around PNe as well (Chesneau et al. 2007; Chesneau 2011) but it is as yet very unclear whether these discs are relics of the discs detected around post-AGB binaries or are much more recently formed. Disc creation and disc evolution should therefore be an important

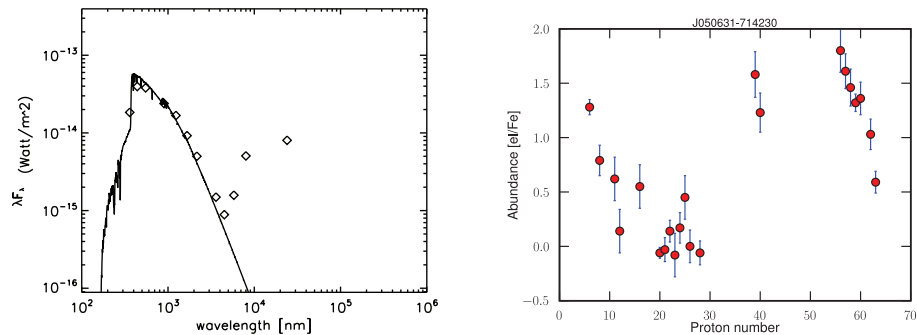


Figure 4. *Left:* the SED of J050631–714230, a post-AGB star in the LMC with a detached shell (van Aarle 2010, submitted). *Right:* the photospheric chemical composition of this strongly *s*-process enriched object of low initial metallicity ($[\text{Fe}/\text{H}] = -1.4$) (van Aarle 2011, in prep.).

ingredient in any binary evolution model with an evolved low- to intermediate-mass object.

The periods and eccentricities found in post-AGB binaries are not too different from that found in Ba stars (Jorissen 1999). These extrinsically enhanced systems harbour a WD which polluted its now seen companion. Despite the orbital similarity, it is very unlikely that there is an evolutionary connection between the post-AGB stars and the Ba star family as no *s*-process enrichment nor carbon-rich circumstellar dust has generally been found in post-AGB stars. The study of the evolutionary connection between post-AGB binaries and the zoo of other binaries with evolved components — Ba stars, symbiotic stars, CH stars (e.g. Jorissen 1999), sdBs, bipolar PNe, CVs, sequence E AGB stars (e.g. Nicholls, Wood, & Cioni 2010, and these proceedings), spiralled-in PNe, etc. — is an additional challenge for many years to come.

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Discussion

Melbourne: Where are these discs forming? Around the primary or the companion?

Van Winckel: The discs are circumbinary. The orbits we found point to semi major axes which are in the order of ~ 1 AU. This is well within the sublimation radius of the primary. The primary is typical $\sim 5000 L_{\text{Solar}}$ and of spectral type G-F. The sublimation radius is ~ 5 -10 AU. The interferometric scales are compliant with the circumbinary nature of the disc.

Maraston: The 21-micron sources are found to be Fe-depleted. Are they particularly α -enhanced? Is there a gradient among the sample? What is the $[\alpha/\text{Fe}]$ ratio for your new SAGE LMC sample?

Van Winckel: The 21 micron sources have central stars with metallicities in the range -0.3 to $-1.0[\text{Fe}/\text{H}]$. The α -enhancement in $[\alpha/\text{Fe}]$ is similar (within the errors) to what is expected from the Galactic evolution. The α elements are, in general, not internally enhanced. For the new s-process rich sample, we have not yet computed detailed abundances for a large ample. Two objects have been analyzed only and both are relatively iron poor. One object has $[\text{Fe}/\text{H}] \sim -1.4$ and the other ~ -1.3 . The α elements are not internally enriched, but both objects are strongly s-process enhanced. We are in the process to analyse a much larger sample, so stay tuned.



Clare Worley, Hans Van Winckel and Tom Lloyd Evans.